EUVL Mask Engineering in the Third Dimension

The Impact of Absorber Sidewall Angles on Imaging Behavior

Tim Fühner, Lawrence S. Melvin III, Yudhishthir Kandel and Weimin Gao

2018 EUVL Workshop   June 11–14

Outline

Motivation

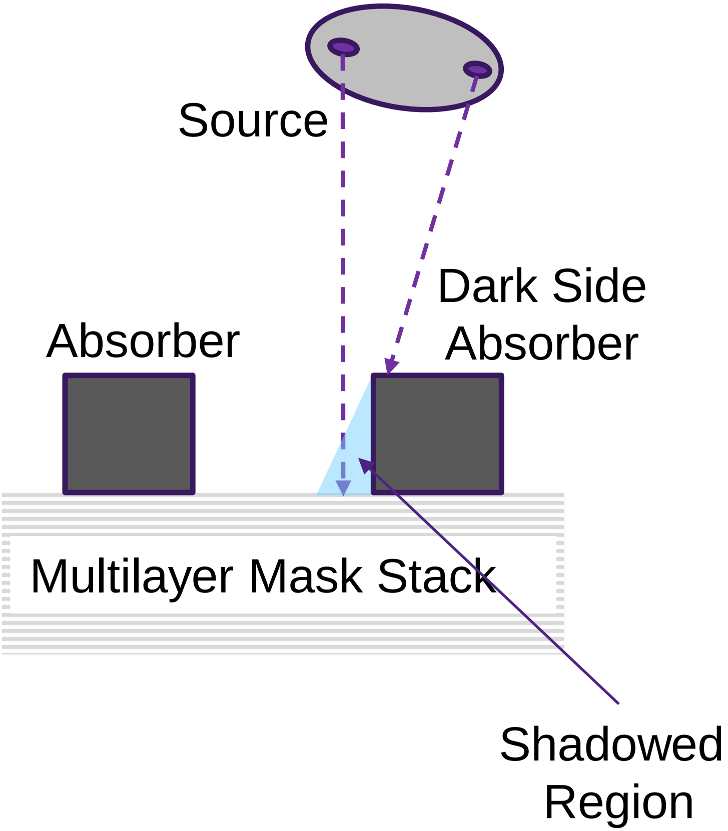
Open (acute angle) Absorber Sidewalls

Undercut (obtuse angle) Absorber Sidewalls

Application to high-k Materials

Conclusions

Introduction

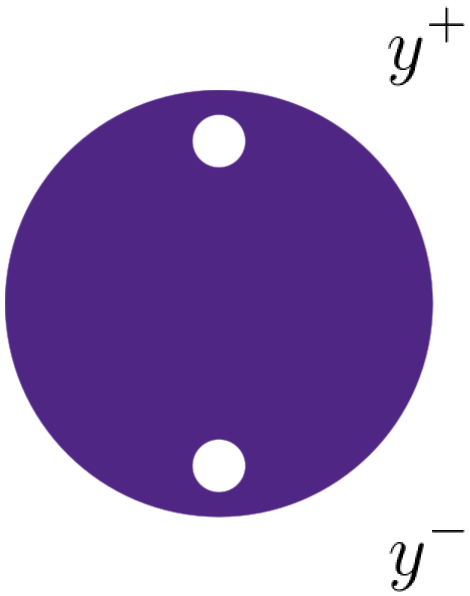


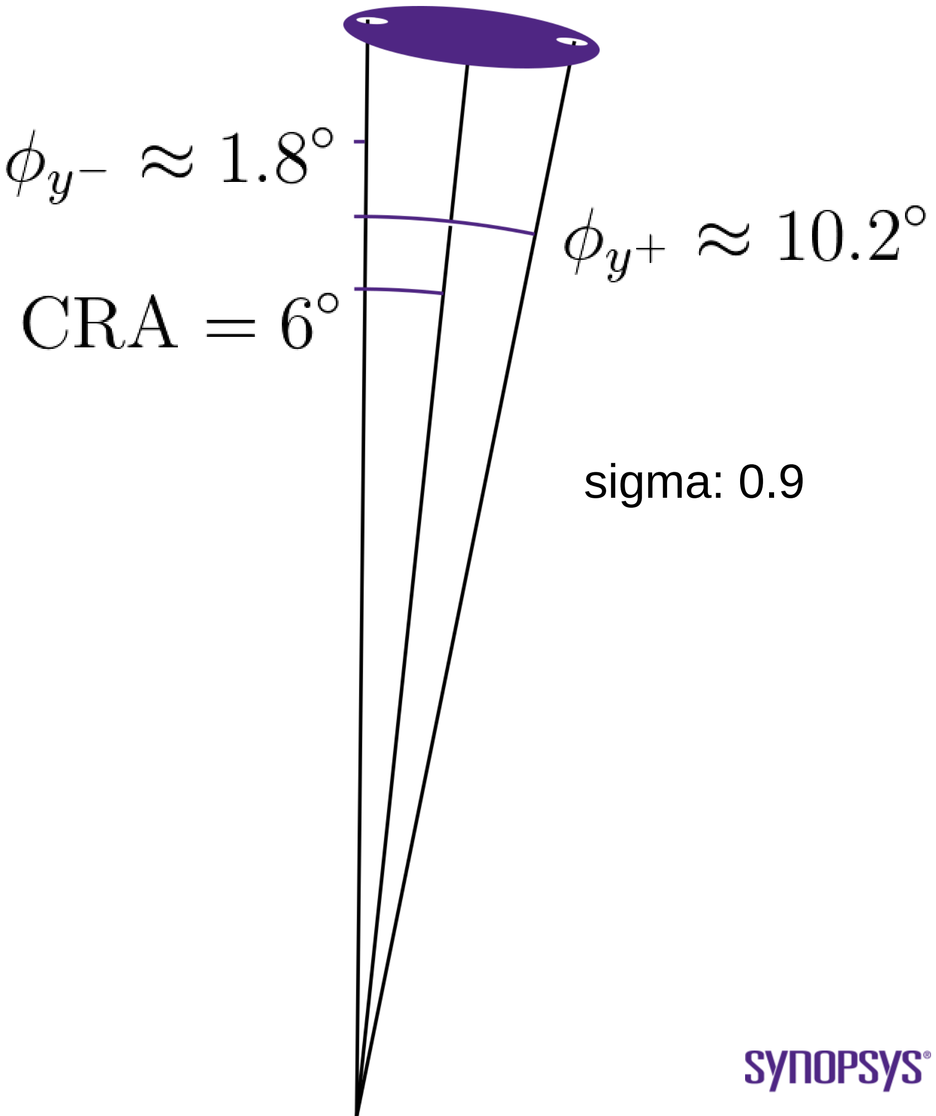
- Mask 3-D effects in EUV are even more critical than in DUV
  - Higher energy, more scattering,
  - Thicker absorber,
  - Chief-ray Angle (CRA) introduces numerous asymmetries, including shadowing

- For state-of-the-art scanners, the CRA is in the *y*-direction
- Any non-vertical line is affected
- Horizontal lines show a pronounced bright and dark side
- Orientation-dependent edge patterning behavior and contrast

Incidence angle-specific asymmetry

- Aggressive off-axis illumination aggravates impact
- Incidence angles on the axis of the CRA are dramatically modified:
  - Bottom source points produce an almost normal incidence
  - Top points lead to relatively large angles



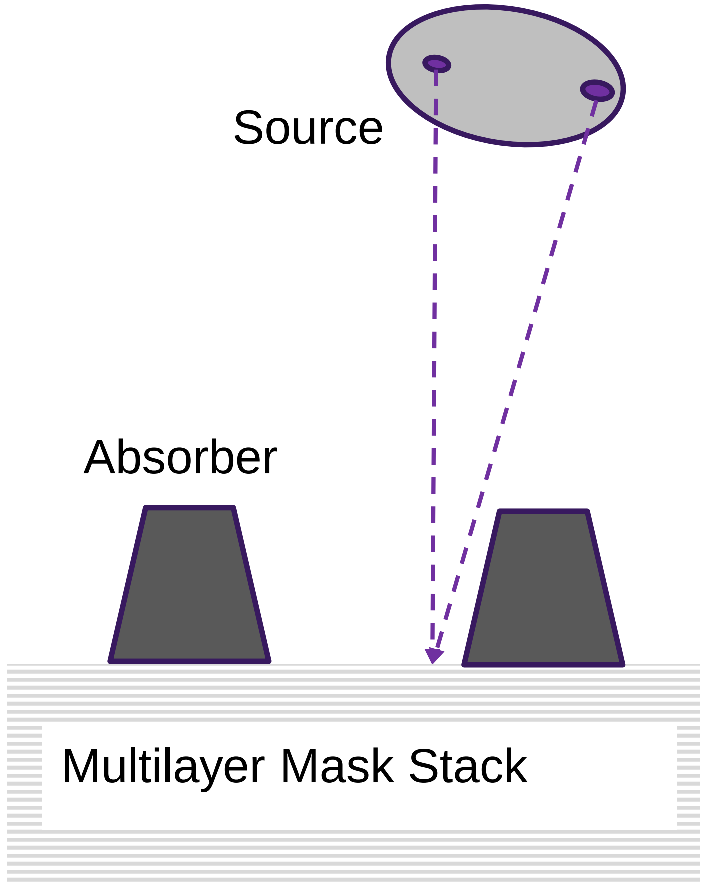


Asymmetry Mitigation Strategy

- Asymmetric source
- Asymmetric mask patterns
- Absorber stack optimization, high-k materials
- Phase shifting masks
- …

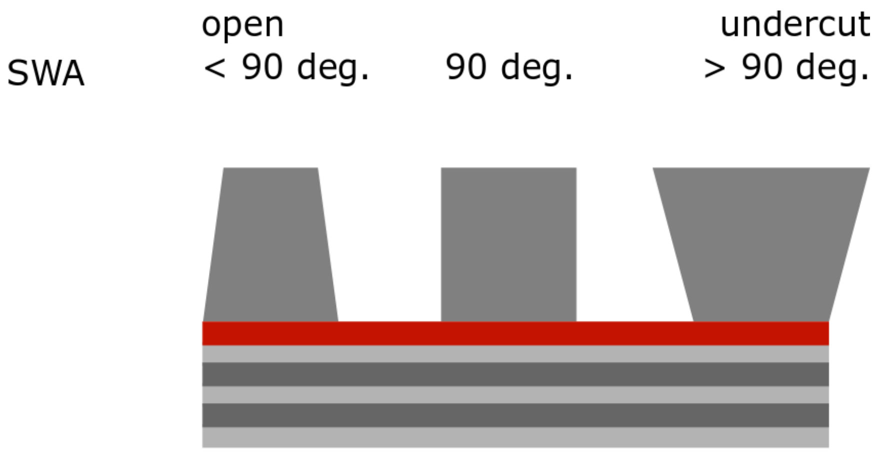
Our proposal

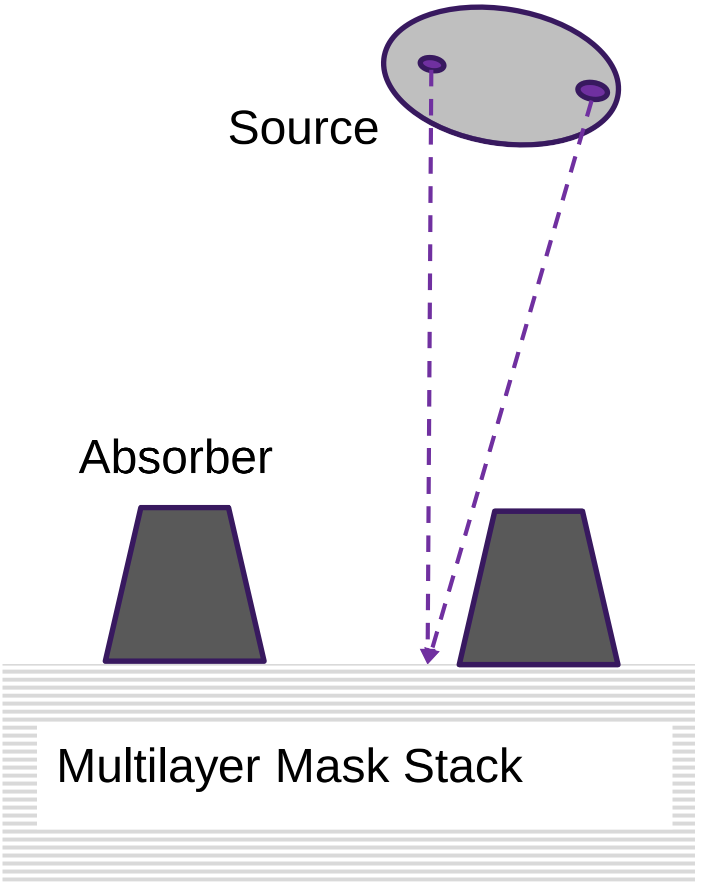
- 3-D topographic correction
- Improve contrast by minimizing edge interactions
- Introduce absorber angle, which is adapted to extreme incidence angle



Sidewall variations

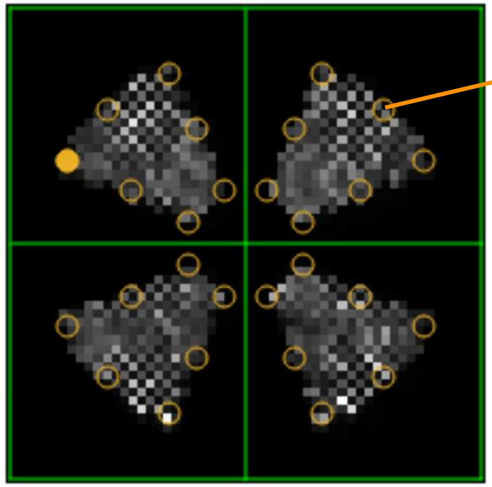
- The largest inclination from a 0.9-sigma source and 6-deg. CRA is about 10 deg.
- Ray-optically, a sidewall angle of about 80 deg. reduces edge scattering



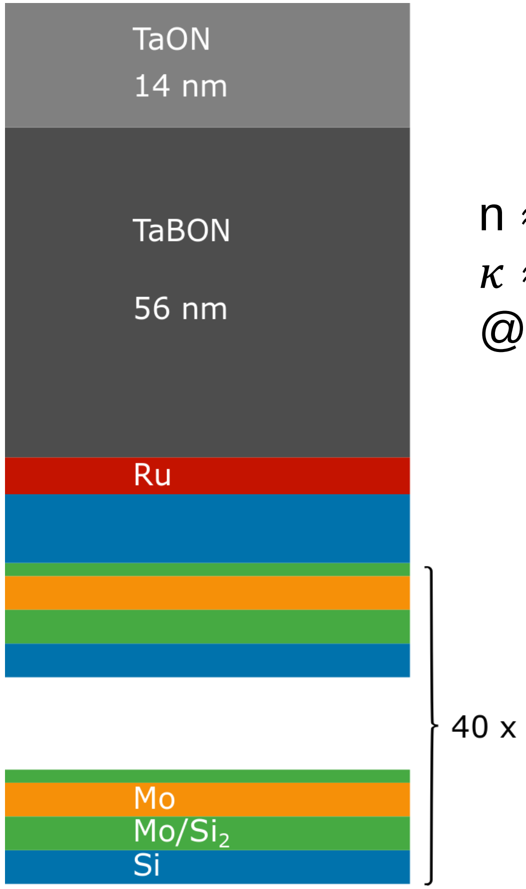


- A range of other angles was experimented with in addition

Simulation Conditions



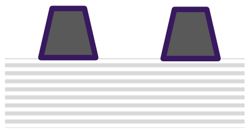
- Source measurement: 0.33-NA 4x NXE:3300 scanner
- Reflector stack with interfacial Mo/Si_2
- All simulations performed with Sentaurus Lithography. EMF simulations: Waveguide and FDTD (for internal field extraction)
- Mask CDs of 12, 14, and 16-nm spaces at a 40-nm pitch in both horizontal and vertical configurations
- Resist simulations conducted with calibrated model

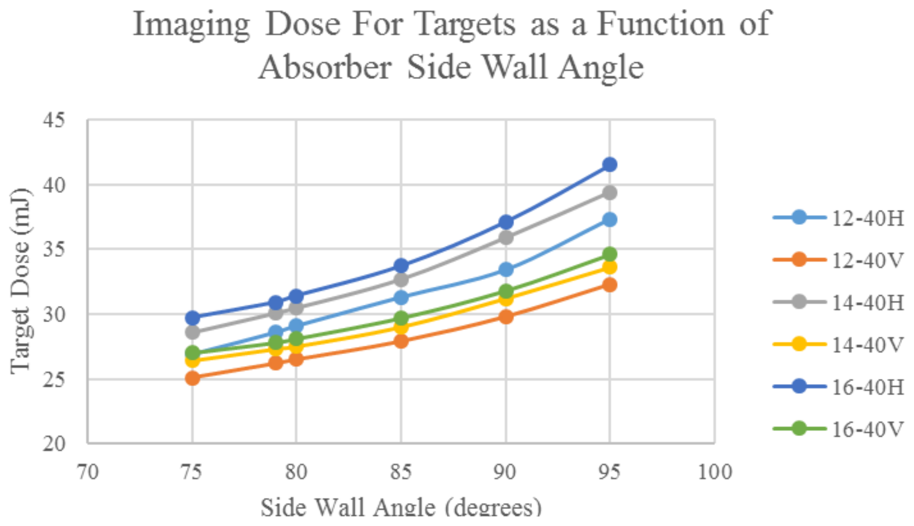


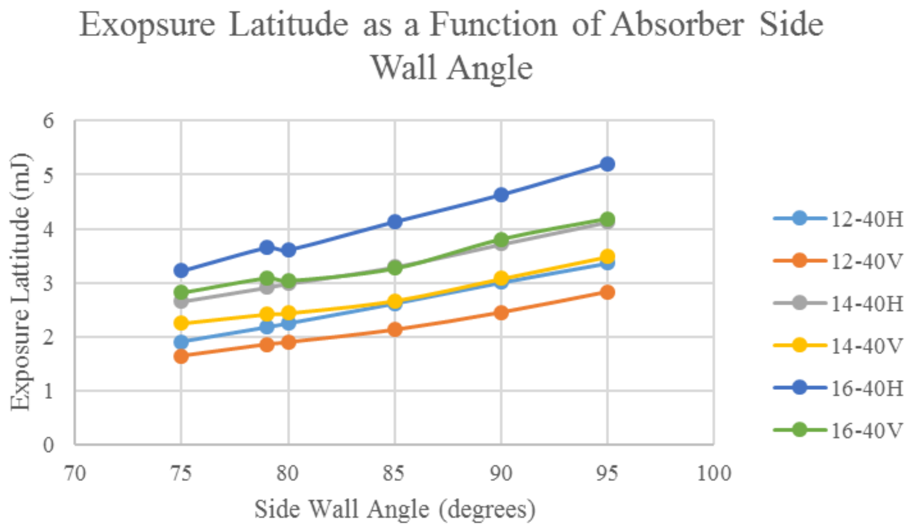
$n \approx 0.95$
$\kappa \approx 0.03$
$@\lambda = 13.5$ nm

Open Sidewalls

Open SWA: Exposure Latitude





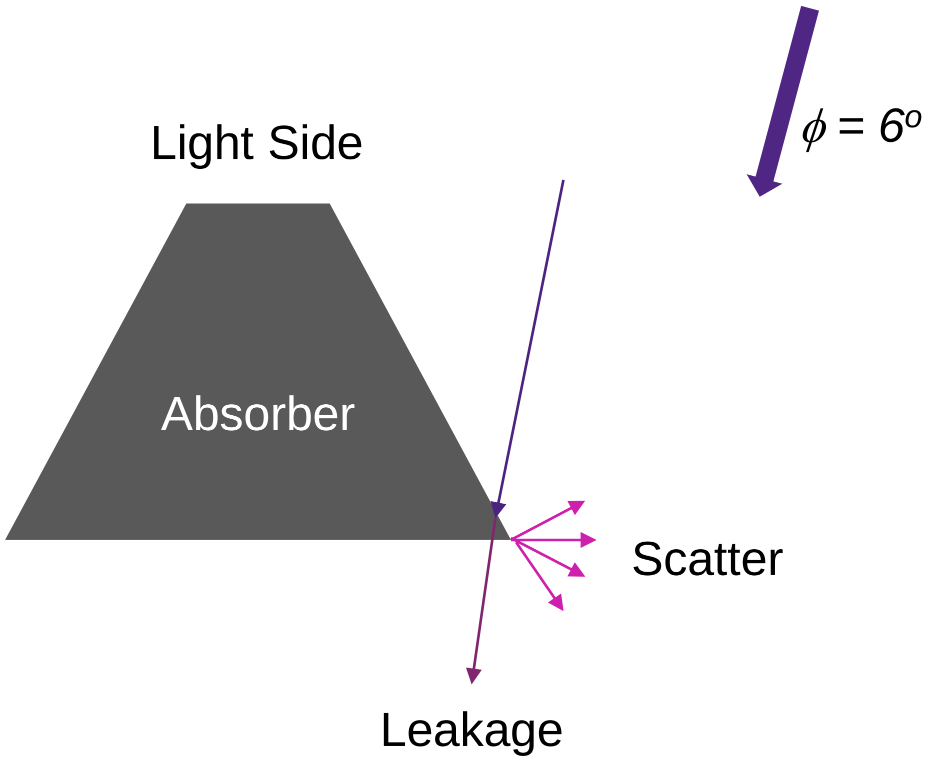


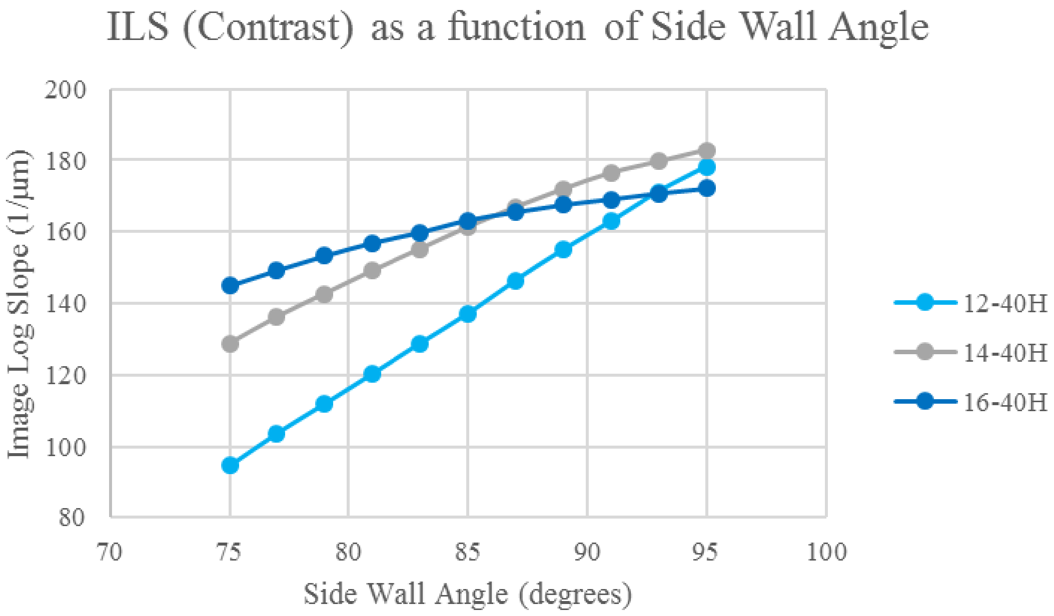
- Dose-to-Size
  - 75º-SWA reduces dose requirement by15–20 % compared with an SWA of 90º
  - Exposure Latitude is proportionally reduced
    - 12 nm case changes from ~8.1% to 6.6%
    - 14 nm and 16 nm cases change ~1% or less

Open SWA: Contrast

- ILS demonstrates a clear trend significant decrease as a function of SWA

- Contrast seems to be blurred by gradual light leakage

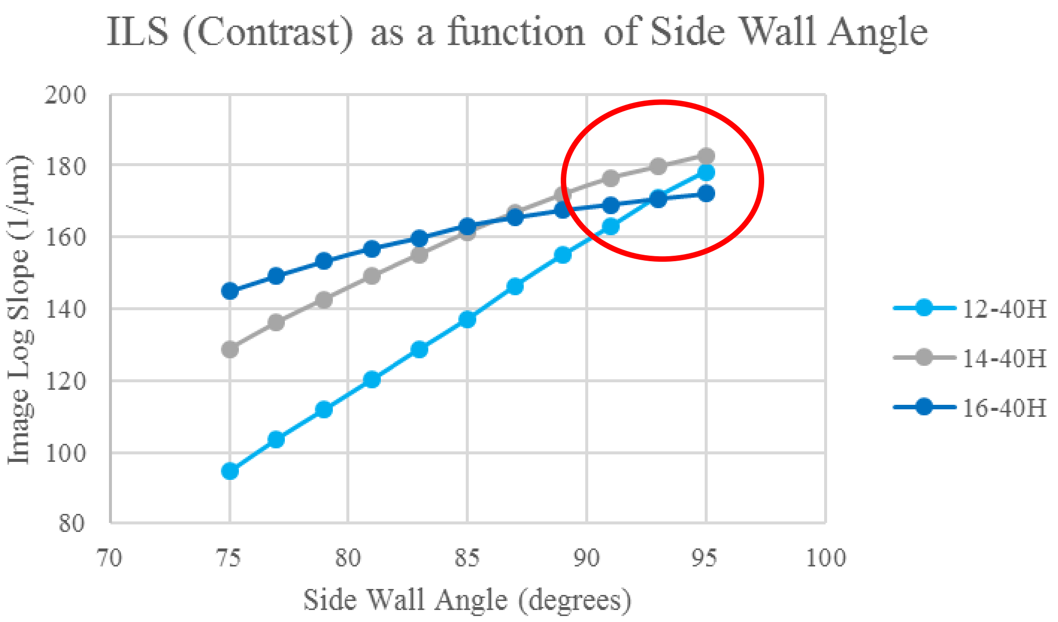




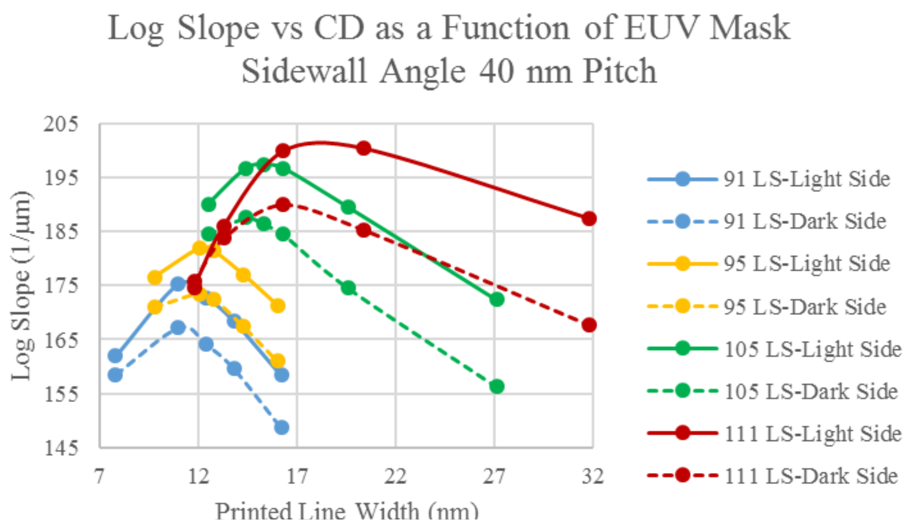
Undercut Sidewalls

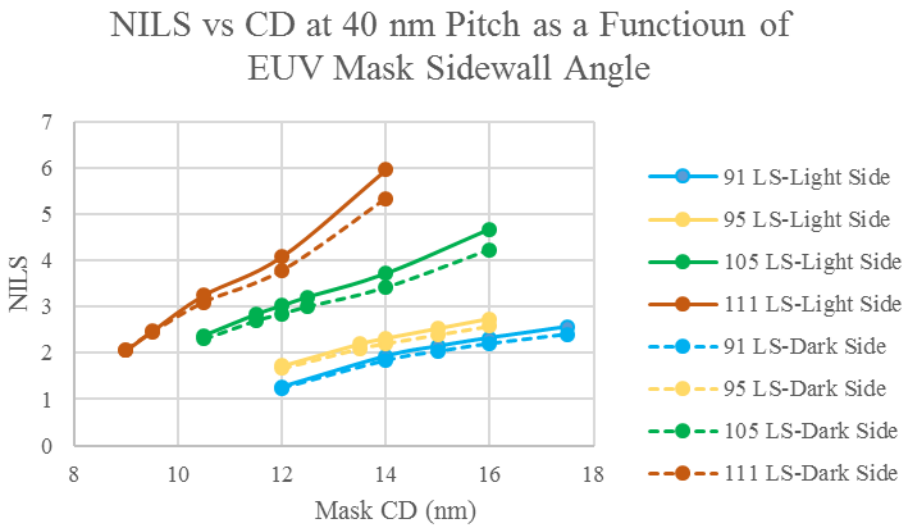
Undercut SWA: Improved Contrast

- SWAs > 90 deg. show better ILS performance
- Exposure latitude increases with undercut SWA
- Depth of focus remains approximately constant as absorber SWA is increased



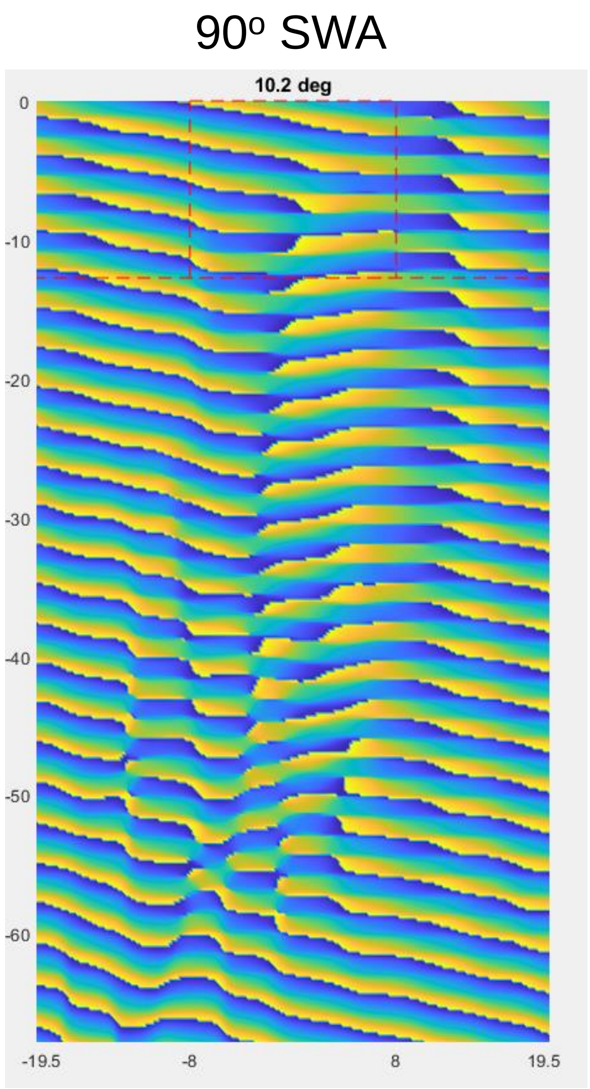
Contrast Bossung Plots SWA

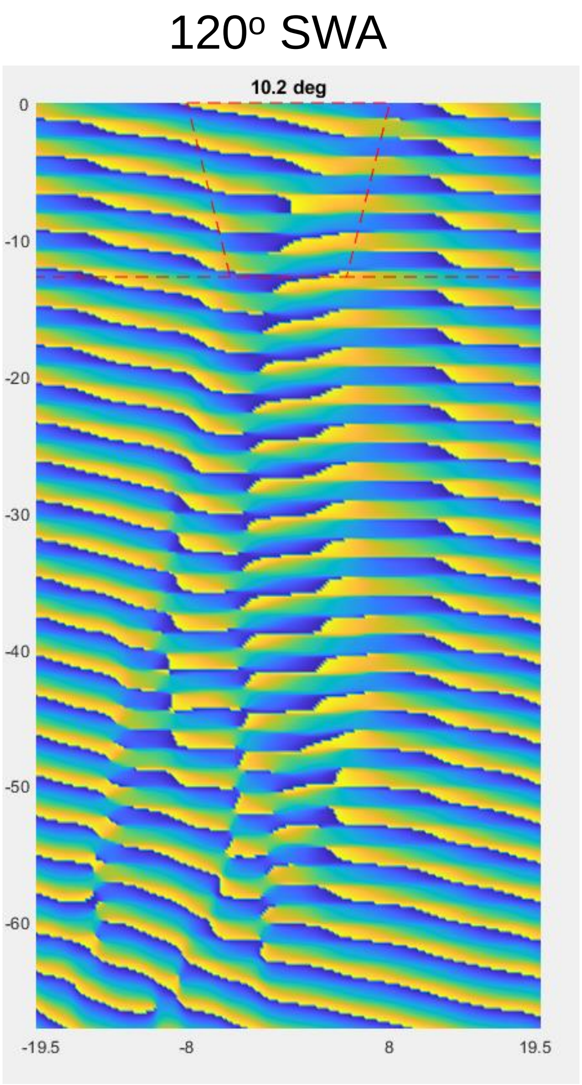




- Both ILS and NILS show an increase as the absorber SWA becomes more undercut
- Contrast improves to a point, then degrades as CD increases
- CD size appears to have an optimal SWA

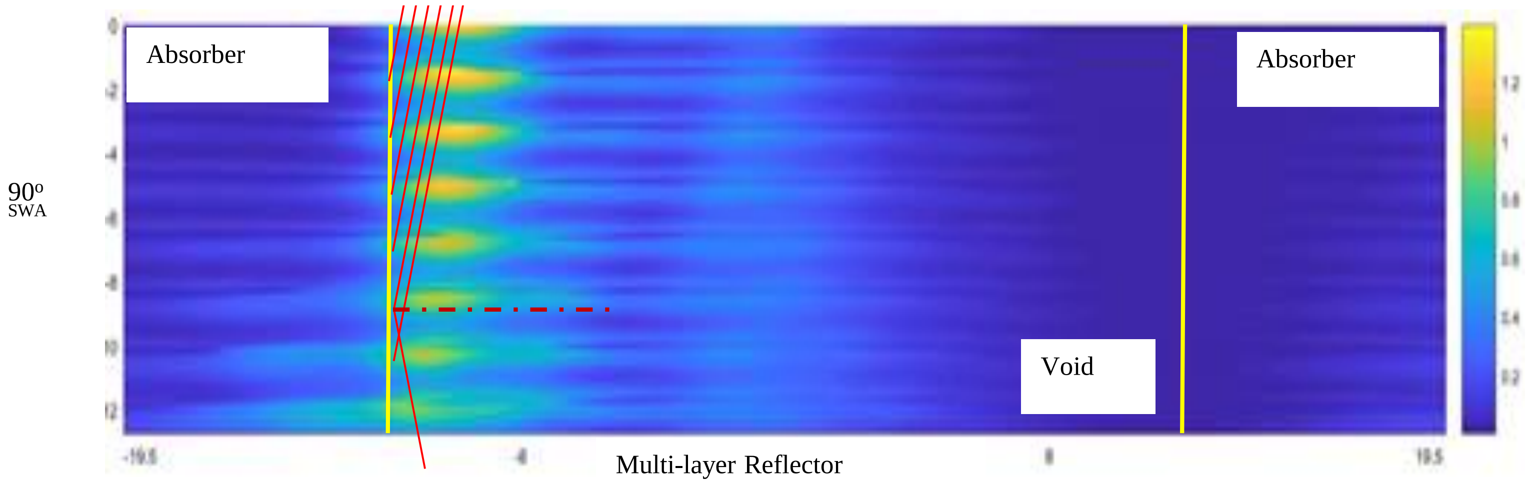
Phase Map of Internal Field





Internal Reflected Fields (E_{xx}) at 90-deg. SWA

- Asymmetric intensity distribution due to CRA
- Absorber reflection for 90°-SWA leads to intensity peak at bright side

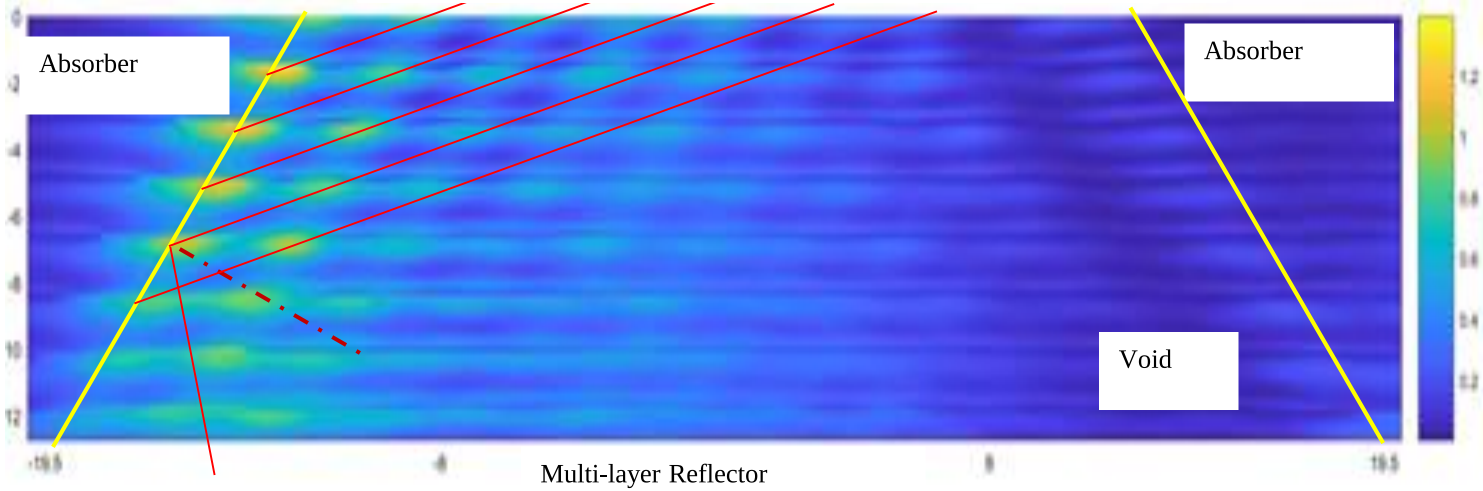


10.2 deg.

Internal Reflected Fields (E_{xx}) at 120-deg. SWA

- Light gets distributed across the space
- Undercut damps bright side intensity peak

120°
SWA



10.2 deg.

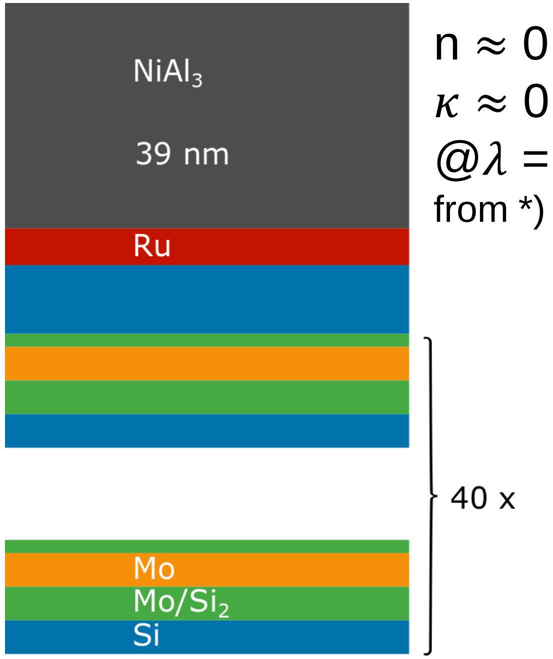
High-k Absorber

High-k Absorber

- Absorber thickness has a significant impact on mask 3-D and asymmetry effects
- High-absorbing material with an index of refraction close to one is sought
- Different Nickel/Aluminium alloys have been proposed
- A recent study* shows a beneficial imaging behavior of $NiAl_3$

- Are the thinner high-k absorbers amenable to sidewall engineering?

- All other conditions unchanged

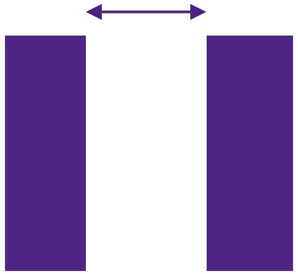


$n \approx 0.98$
$\kappa \approx 0.06$
$@\lambda = 13.5$ nm
from *)

*) Luong, V., Philipsen, V., Hendrickx, et al. (10.3390/app8040521)

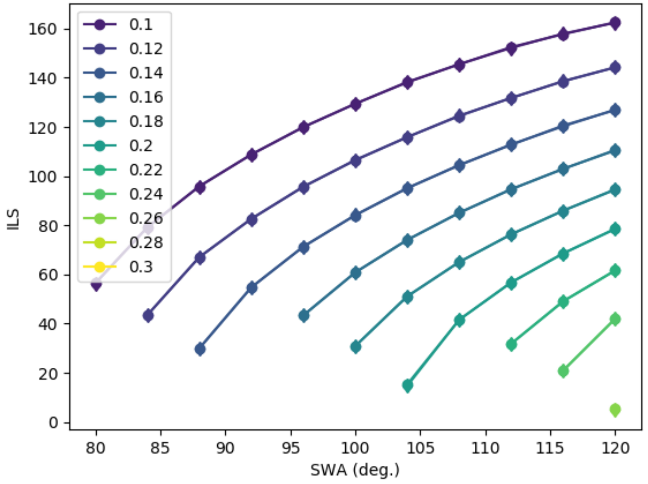
Sidewall angle vs ILS

target CD

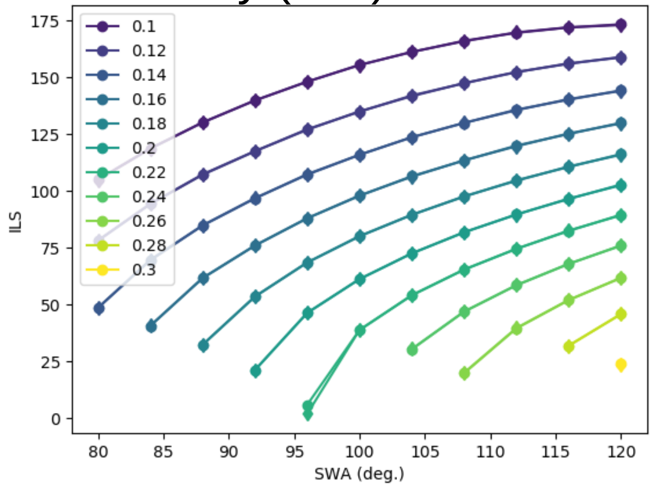


intensity (a.u.)

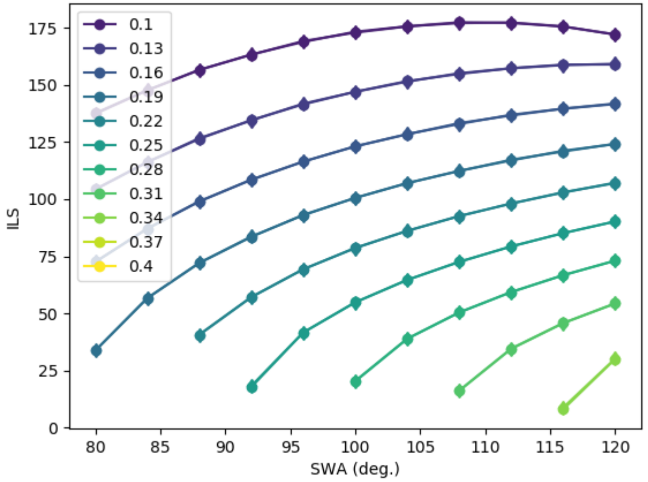
12 nm



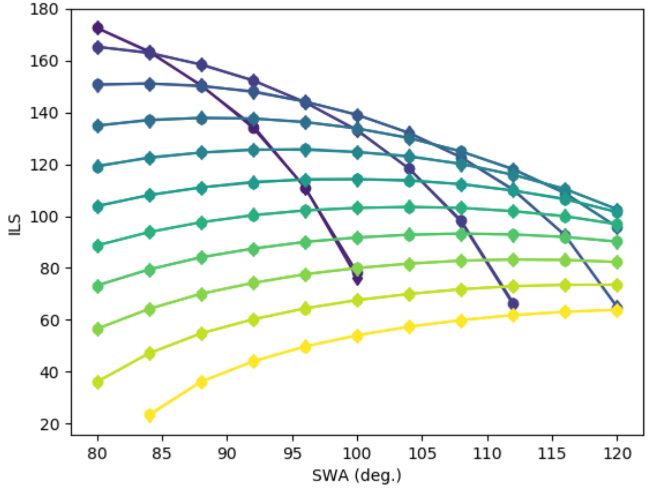
14 nm



16 nm

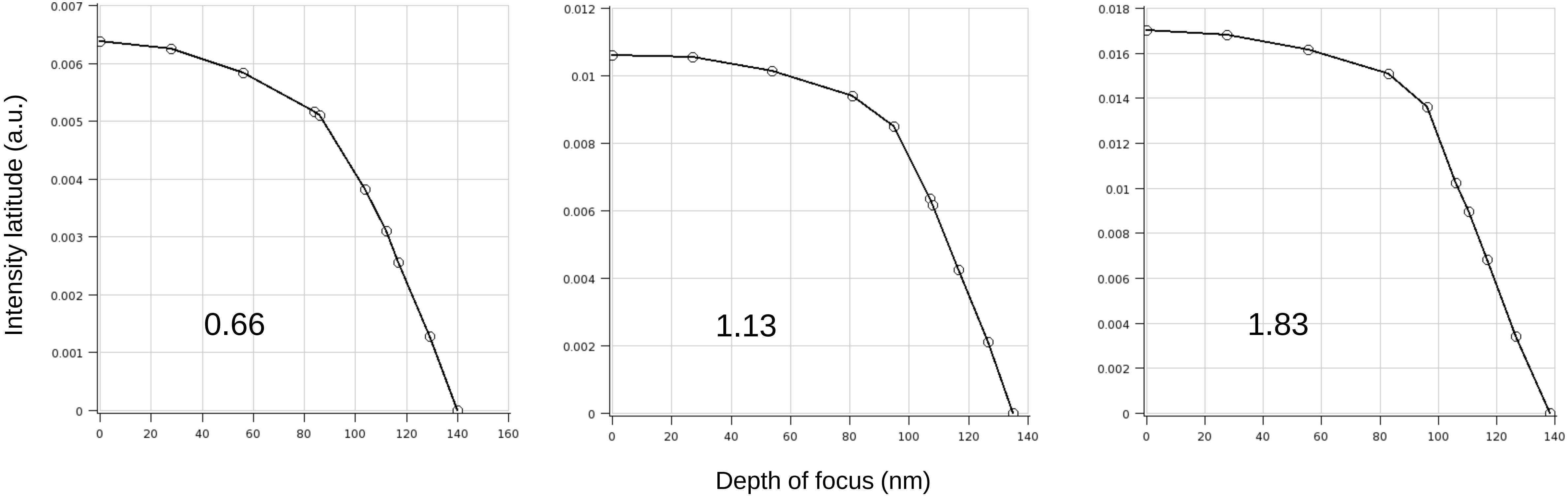


24 nm



SYNOPSYS®

High-k Absorber: Latitude of 12-nm CD Target

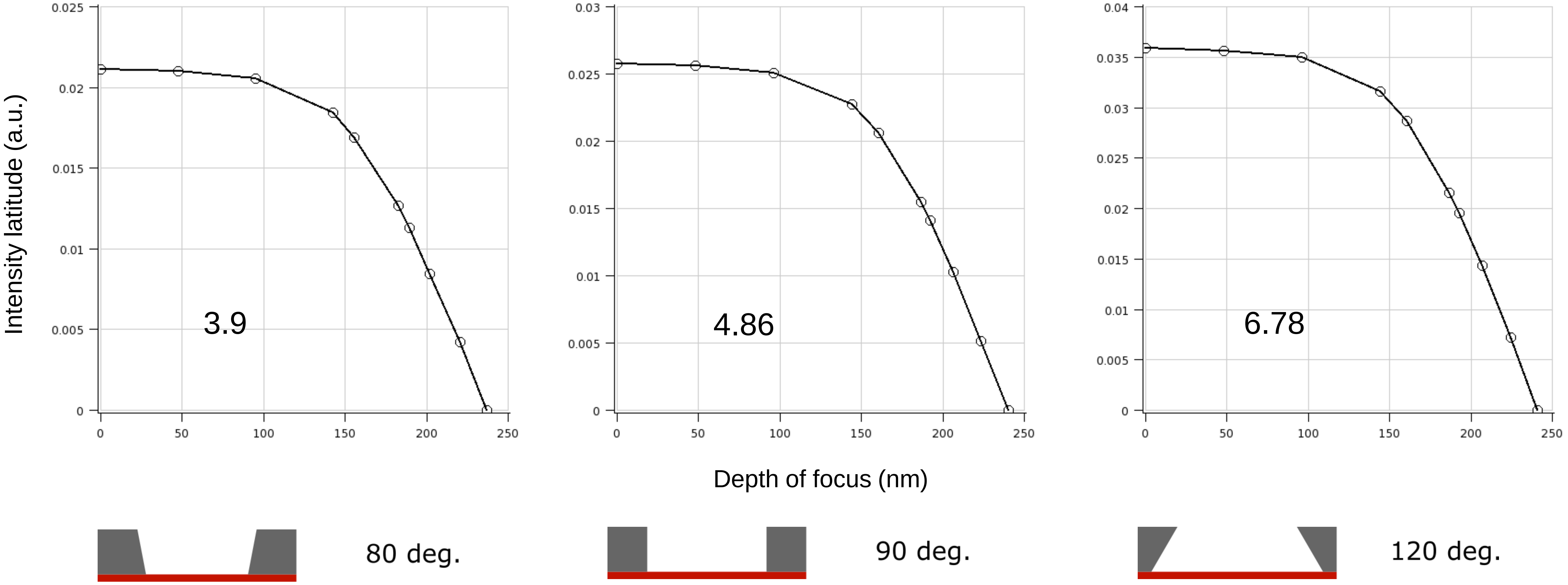


80 deg.

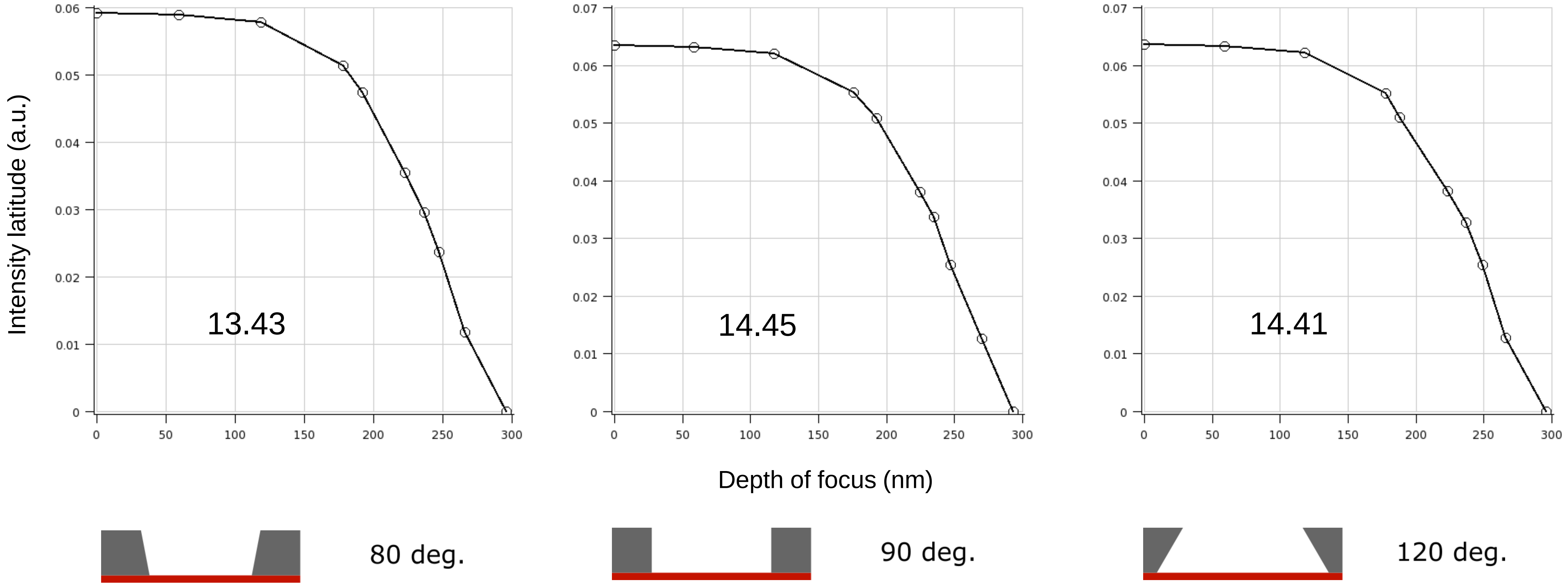
90 deg.

120 deg.

High-k Absorber: Latitude of 16-nm CD Target



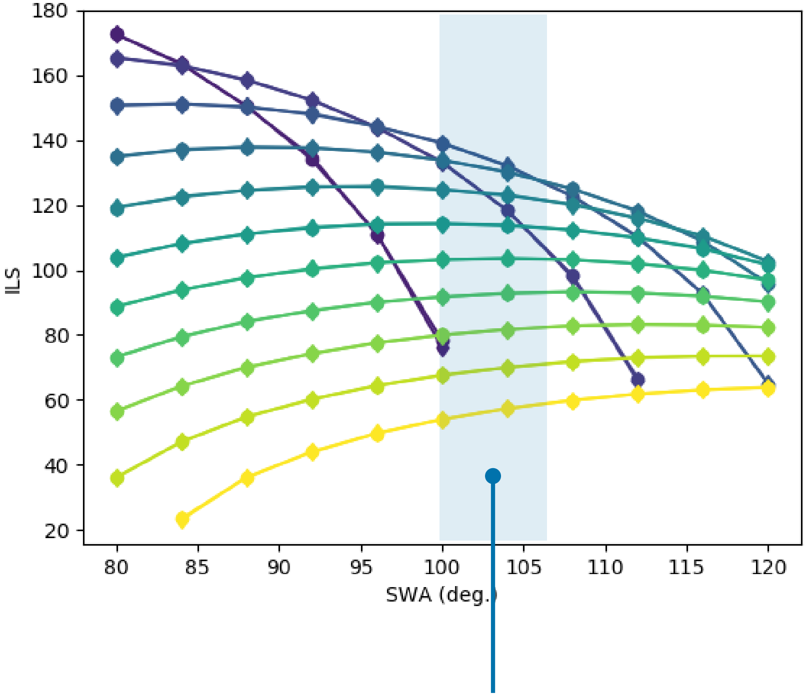
High-k Absorber: Latitude of 24-nm CD Target



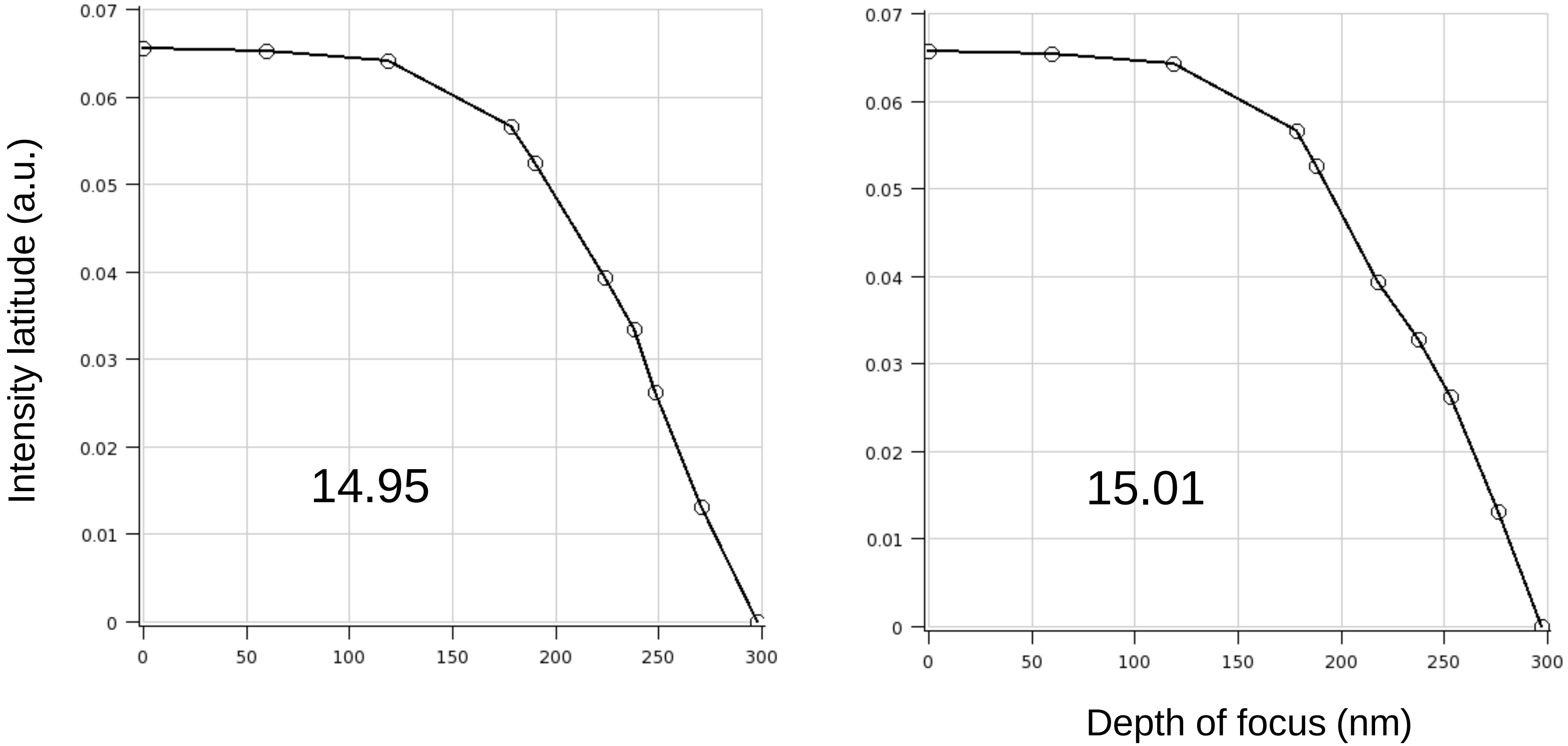
SYNOPSYS®

Sweet Spot between 100 and 105 deg.

Revisiting ILS plot



Sweet spot

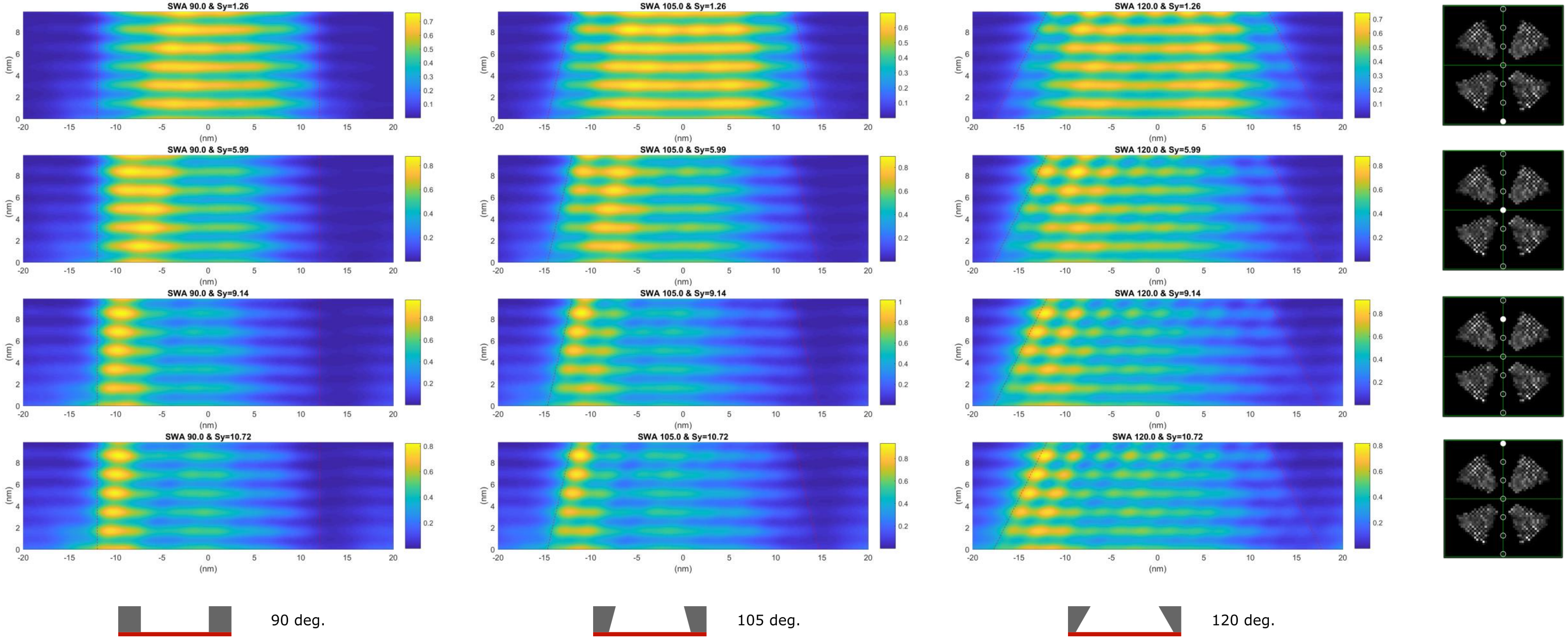


100 deg.

105 deg.

SYNOPSYS®

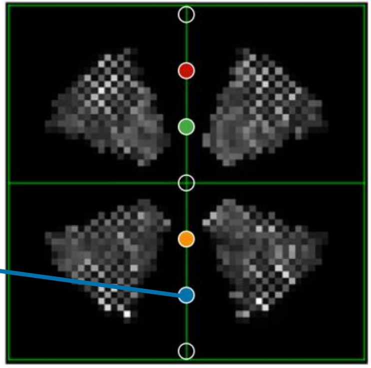
24-nm CD: Internal Reflected Fields

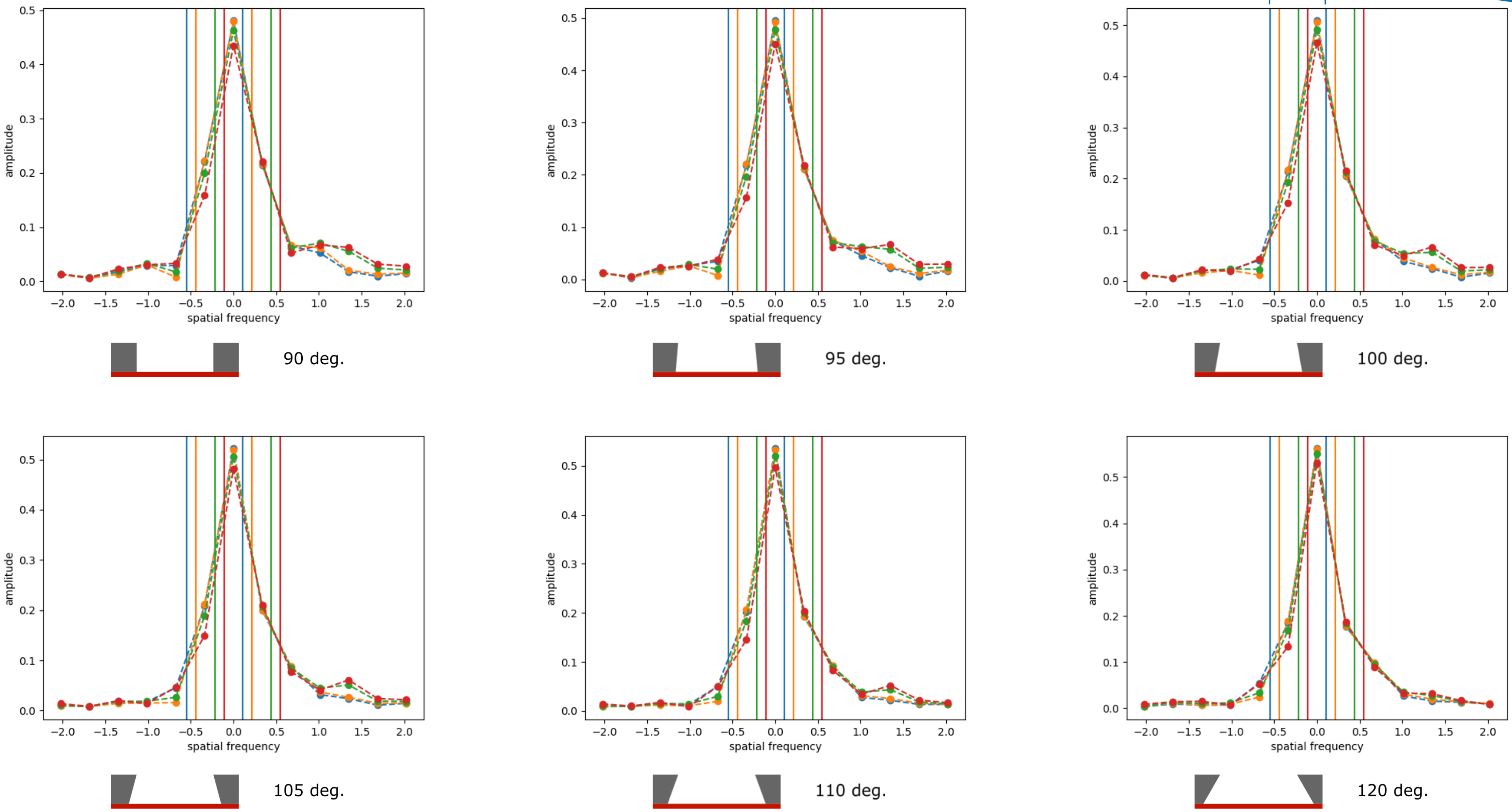


SYNOPSYS®

24-nm CD: Diffraction orders

shifted band limit

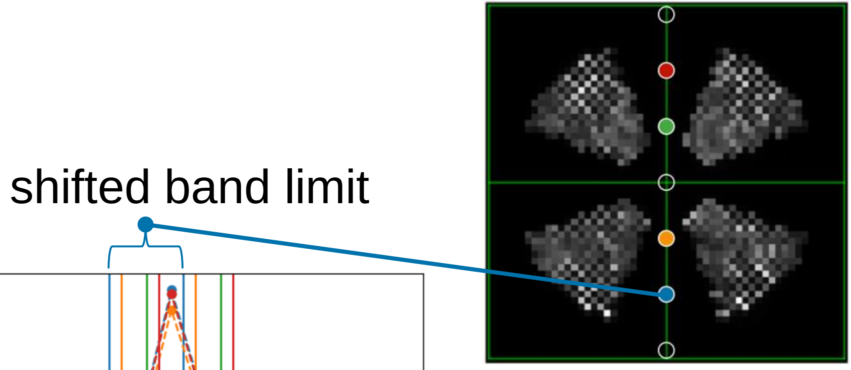


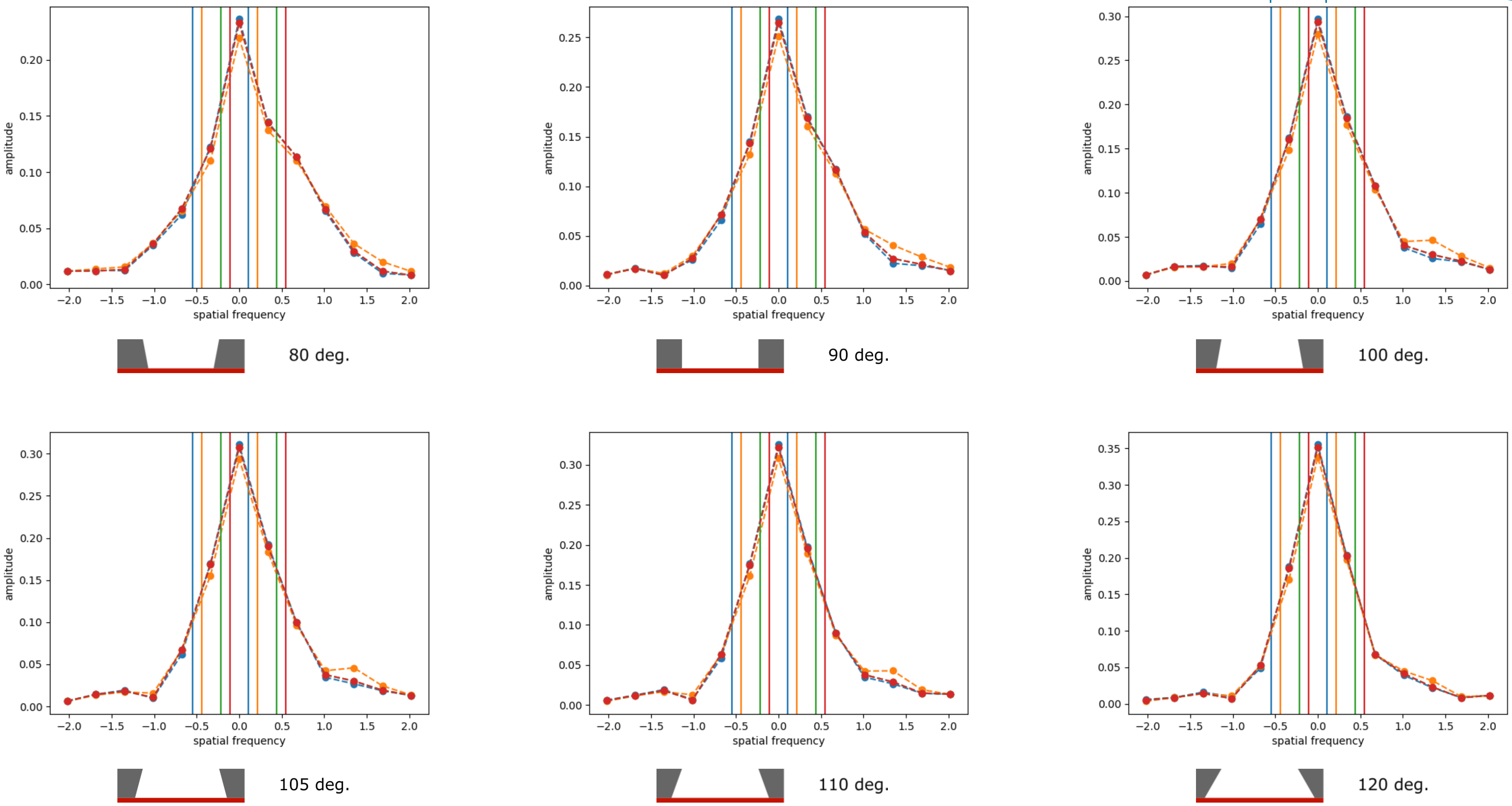


diffraction orders due to different incidence angles (colors)

E_{xx} amplitudes shown

12-nm CD: Diffraction orders





diffraction orders due to different incidence angles (colors)

SYNOPSYS®

Conclusions

- Topography optimization of the absorber can help increase process margins and improve contrast.
- Impact of 3-D mask engineering is strongly feature-dependent.
- High-k material stacks are amenable to sidewall engineering.

- Manufacturablity, especially etch control, still needs to be validated.
- Applicability to 0.55-NA systems to be studied.

Acknowledgements

We would like to acknowledge Vicky Philipsen and Eric Hendrickx from *imec* who generated the wafer data used to construct the Sentaurus Lithography model in this study.

SYNOPSYS®

Silicon to Software™